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# RESPONSE OF A JET TRAINER AIRCRAFT TO ROUGHNESS OF THREE RUNWAYS

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## SUMMARY

An investigation has been conducted to determine the acceleration response of a jet trainer airplane and to correlate runway roughness with the response. Acceleration data were obtained during taxi runs at constant speed on three runways having different roughness characteristics. In general, airplane acceleration increased with speed for the three runways and was higher at the nose than at the center of gravity. Direction of taxiing had no significant effect on the acceleration response. Pilot opinion of the relative roughness of the runways was in agreement with airplane-acceleration-response measurements. Airplane response and runway spectra were in general agreement in that the lowest response was measured on the runway which was indicated by the profile spectra to be significantly smoother than the other two. However, the runway spectra did not provide a good indication of the relative response of the airplane on the other two runways for which the spectra showed only a small difference in roughness. Airplane transfer functions, computed as the ratio of the output acceleration spectra to the input runway spectra varied significantly between repeated runs for similar test conditions.

## INTRODUCTION

Because of the importance of runway roughness to the design and operation of airplanes, a number of studies have been made to evaluate the roughness characteristics of existing runways, to define acceptable levels of roughness, and to provide information on airplane responses to runway roughness. (See, for example, refs. 1 to 8.) As a continuation of the study of the responses of airplanes to runway roughness, an investigation has been made to determine the response characteristics of a jet trainer airplane. Normal accelerations at the center of gravity and near the nose were measured during taxi runs at constant speed on three runways having different roughness characteristics. Elevation profiles along the center lines of the runways were measured for use in defining the runway roughness characteristics.

The results of the investigation are presented in the form of profiles and power spectra of the runways, time histories of airplane normal-acceleration response, maximum and root-mean-square acceleration, power spectra of acceleration, and airplane transfer functions. The roughness power spectra are compared with spectral levels which have been previously suggested as criteria for "new construction" and "needs repair." In addition, the degree of correlation obtained for the indication of roughness based on airplane response, roughness power spectra, and pilot opinion is discussed.

## SYMBOLS

$a_n$ — positive or negative value of airplane normal-acceleration increment for a specific taxi run, g units

$a_{n,max}$ — maximum positive or negative value of airplane normal-acceleration increment for a specific taxi run, g units

$f$ — frequency, cps

$g$ — acceleration due to gravity

$L$ — length, ft

$|T(f)|^2$ — amplitude squared of frequency-response function, $\left|\frac{g}{ft}\right|^2$

$x$ — runway station, ft

$\Delta x$ — interval spacing between runway stations, ft

$y$ — elevation of runway, ft

$\delta$ — deviation of elevation of runway from midpoint of a straight line of length $L$ which has its end points resting on runway profile

$\lambda$ — wavelength, ft

$\sigma_{a_n}$ — root-mean-square value of airplane normal-acceleration increment, g units

$\sigma_\delta$ — root-mean-square central deviation between straight line and runway elevation profile, ft

$\Phi_{a_n}(f)$ — power-spectral-density function of airplane acceleration increment, $g^2/cps$

$\Phi_h(f)$ — power-spectral-density function of runway elevation for a specific taxiing speed, $ft^2/cps$

$\Phi_h(\Omega)$ — power-spectral-density function of runway elevation, $ft^2/radian/ft$

$\Omega$ — reduced (spatial) frequency, $2\pi/\lambda$, radians/ft

## APPARATUS AND METHOD

### Airplane

A photograph of the two-place jet trainer airplane used for the investigation is shown in figure 1, and a three-view drawing of it is shown in figure 2. The airplane gross weight varied from 10,000 to 11,000 pounds, and the

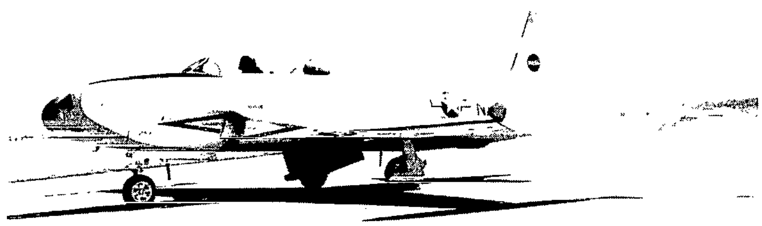


Figure 1.- Photograph of test airplane. L-62-7530

center of gravity varied from 26.7- to 27.6-percent mean aerodynamic chord during the tests. The airplane was equipped with wing-tip fuel tanks, which were empty for most of the tests. Tire pressure was 130 lb/sq in. for the main gear and 80 lb/sq in. for the nose gear. These pressures were recommended for a take-off gross weight of 12,500 pounds.

### Instrumentation

The airplane was equipped with two strain-gage acceleration transmitters, a tachometer, a gun camera, a 1/10-second timer, and an oscillograph. One acceleration transmitter was located near the center of gravity of the airplane about 18 inches ahead of the main landing gear, and the other transmitter was located in the fuselage over the nose wheel about 170 inches ahead of the main gear. The accelerometers at the center of gravity and nose had natural frequencies of 10 and 9.8 cps, respectively, were 0.7 critically damped, and had ranges from -1g to 3g. A tachometer consisting of a small electric generator driven by the nose wheel was used to supply the ground-speed signal for the oscillograph and for an indicator in the pilot's compartment.

A gun camera mounted on top of the instrument panel with the lens axis perpendicular to the airplane fuselage axis was used to take pictures of marker boards located along the runway for the purpose of synchronizing the data record with the profile of the runway test section. The exposure of each picture was marked on the oscillograph record by means of an electrical signal actuated by the shutter of the camera.

### Test Procedures

Normal acceleration and ground speed were continuously recorded during constant-speed taxiing runs over a 3,000-foot portion of three runways. Of

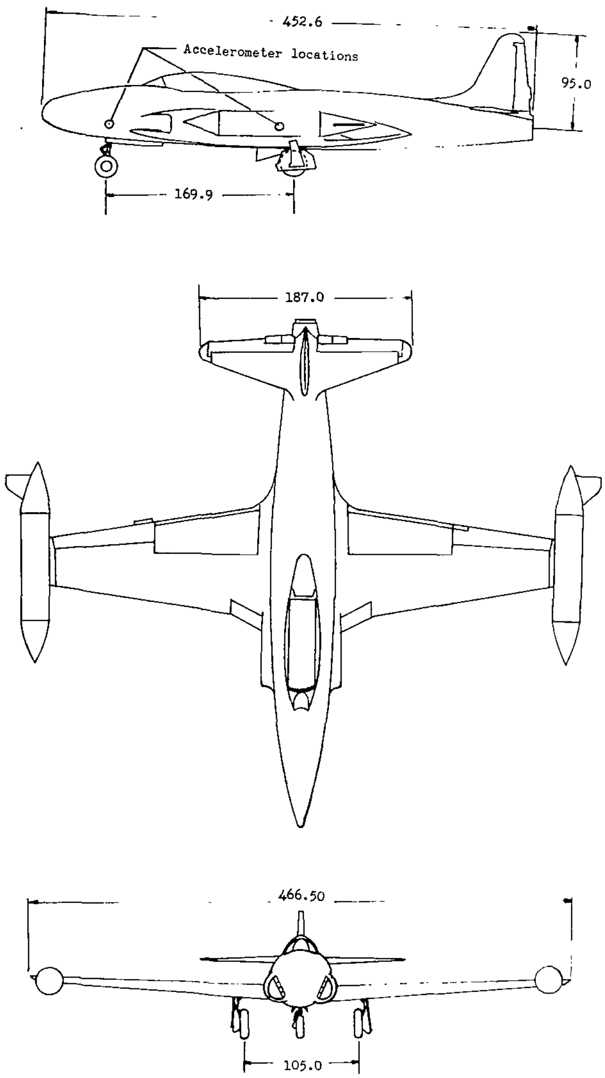


Figure 2.- Three-view drawing of test airplane. (All dimensions are in inches.)

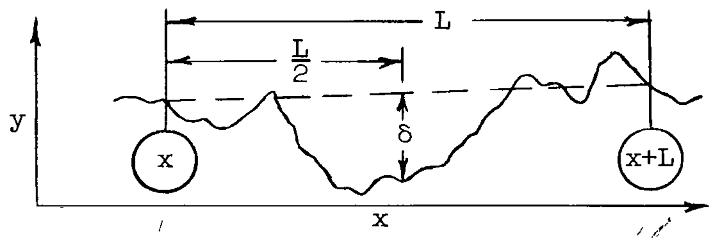
the two military runways, one (runway A) was 10,000 feet long and 150 feet wide, and the other (runway B) was 12,000 feet long and 200 feet wide. Runway C, a newly constructed commercial runway, had a length of 10,000 feet and a width of 150 feet. Acceleration response was measured at both the center of gravity and the nose while the airplane was taxied over runways A and B but was measured only at the center of gravity for the investigation of runway C. The track of the airplane nose wheel was along the center line of the runway test sections, which were in the middle third of the runway length. There were no intersections of other runways with the test sections. The runs were usually repeated in opposite directions at about the same speed, and in some instances a few runs were repeated in the same direction. The taxi runs covered a speed range from approximately 15 knots to slightly over 100 knots. Light steady braking was necessary to maintain speed because of excess idle thrust for the two runs at approximately 15 knots. The control stick was held forward for all runs. All taxi runs, with the exception of one series, were made with flaps deflected 30°, the normal position for take-off. One series of tests on runway B was made in the landing configuration (i.e., flaps fully deflected (45°) and dive brakes extended) to determine if any significant changes in airplane response resulted from the different configuration. Tests were made during periods of either calm or light winds. The elevation profiles of the center line of the test portion of the runways were surveyed at 2-foot intervals with a level, a rod, and a steel tape.

## DATA ANALYSIS

### Runway Roughness Characteristics

Power spectra of the runway profiles were computed by the basic method of reference 4 from elevation measurements obtained at 2-foot intervals from surveys along the center lines of the runways. As in past work (for example, refs. 1, 2, and 4 to 8), 40 uniformly spaced power estimates were computed throughout the reduced-frequency range from 0.039 to 1.571 radians per foot (160- to 4-foot wavelengths). However, it has been found by the National Aeronautics and Space Administration and other organizations that the first power estimate ($\Omega = 0.039$ and $\lambda = 160$ feet for $\Delta x = 2$) may be seriously in error because of a contaminating effect of grades or very long wavelength irregularities in the runway profile. (See ref. 9.) Consequently, to obtain reliable spectral estimates at this 160-foot wavelength and also to extend the spectra to longer wavelengths, additional spectra were computed with a $\Delta x$ of 8 feet. These spectra yielded 40 power estimates over the wavelength range from 640 to 16 feet. The two sets of power estimates (based on a $\Delta x$ of 2 and 8 feet) were then used to define the power spectrum for wavelengths from 320 to 4 feet.

Runway surface irregularities were also determined as the deviation $\delta$ of the elevation of the runway from the midpoint of a straight line of length $L$ which has its end points resting on the runway profile.




The deflections were computed from the equation

$$\delta = \frac{y_{(x)} + y_{(x+L)}}{2} - y_{\left(x+\frac{L}{2}\right)}$$

where $y$ is the elevation and $x$ is the runway station. (Subscripts in parentheses indicate values of $y$ at that point.) Successive values of $\delta$ for a particular $L$ were computed for 2-foot increments along the test sections, and root-mean-square deviation values $\sigma_\delta$ were computed. This procedure was repeated for lines of several different lengths ranging from 12 to 200 feet.

## Acceleration Measurements

The nose acceleration occasionally contained high-frequency oscillations (about 16 cps) which were not of interest in the present investigation. Consequently, these high-frequency oscillations were eliminated by fairing, and the record was read at 1/20-second intervals.

The spectra of the incremental normal accelerations $\Phi_{a_n}(f)$ were computed by the method of reference 10. Forty-one uniformly spaced power estimates were computed over the frequency range from 0 to 10 cps. The data were also used to obtain root-mean-square (rms) values of acceleration increment $\sigma_{a_n}$.

## Transfer Function

The amplitude squared of the airplane frequency-response functions of acceleration to runway roughness were computed from the relation (ref. 2)

$$|T(f)|^2 = \frac{\Phi_{a_n}(f)}{\Phi_h(f)}$$

where $\Phi_{a_n}(f)$ is the spectrum of the airplane normal-acceleration response and $\Phi_h(f)$ is the spectrum of the runway roughness along the center line. The foregoing relation for the transfer function assumes that the system is linear and that the response is due to a single input. As is well known, however, the landing gears of airplanes are highly nonlinear. Also, runway roughness constitutes not a single input but, rather, consists of three inputs through the nose gear and the two main gears. In order to determine the extent to which these violations would nullify the practical application of the transfer functions in calculating airplane response, the present measurements were used to provide information on the consistency of the functions for repeated test conditions and under different levels of roughness.

## Accuracy

The runway elevations were read from a precision surveyor's level and are estimated to be accurate within ±0.002 foot. This accuracy is sufficiently high to make the errors negligible insofar as the elevation profiles are involved. The errors may, however, have some effect on the runway roughness spectra. Although there is no precise method available for determining the effect of this error on the spectra, estimates of the ratio of the reading error to the computed spectra have been made as an indication of the effect by assuming that the spectrum of reading error is flat throughout the frequency range covered. For the smoothest runway, which would be most affected by the error, the ratio was about 0.8 for wavelengths from 4 to 8 feet and rapidly decreased with increasing wavelengths greater than 8 feet. It is thought, therefore, that the runway roughness spectra are essentially unaffected by the error for wavelengths larger than about 10 feet but that they may be significantly in error for shorter wavelengths.

On the basis of film-reading errors and instrument accuracy, it is estimated that the maximum values of acceleration are accurate within ±0.02g. The accuracy of the root-mean-square accelerations is thought to be within ±0.005g.

An analysis similar to that discussed in the preceding paragraph indicated that the errors would have a negligible effect on the acceleration spectra.

The reliability of the transfer functions is affected by errors in both the acceleration and runway elevation readings. A general discussion of the effect of errors on the computation of transfer functions is given in reference 11. In the present case, it is thought that the effects of reading and instrument errors are secondary to other factors which affected the accuracy of the transfer functions, as is discussed in a later section.

## RESULTS AND DISCUSSION

### Runways

Characteristics of test sections.- Profiles of the test sections of the runways are shown in figure 3. The 3,000-foot test sections of runways A and B had very little grade and varied in elevation by less than 1 foot, whereas

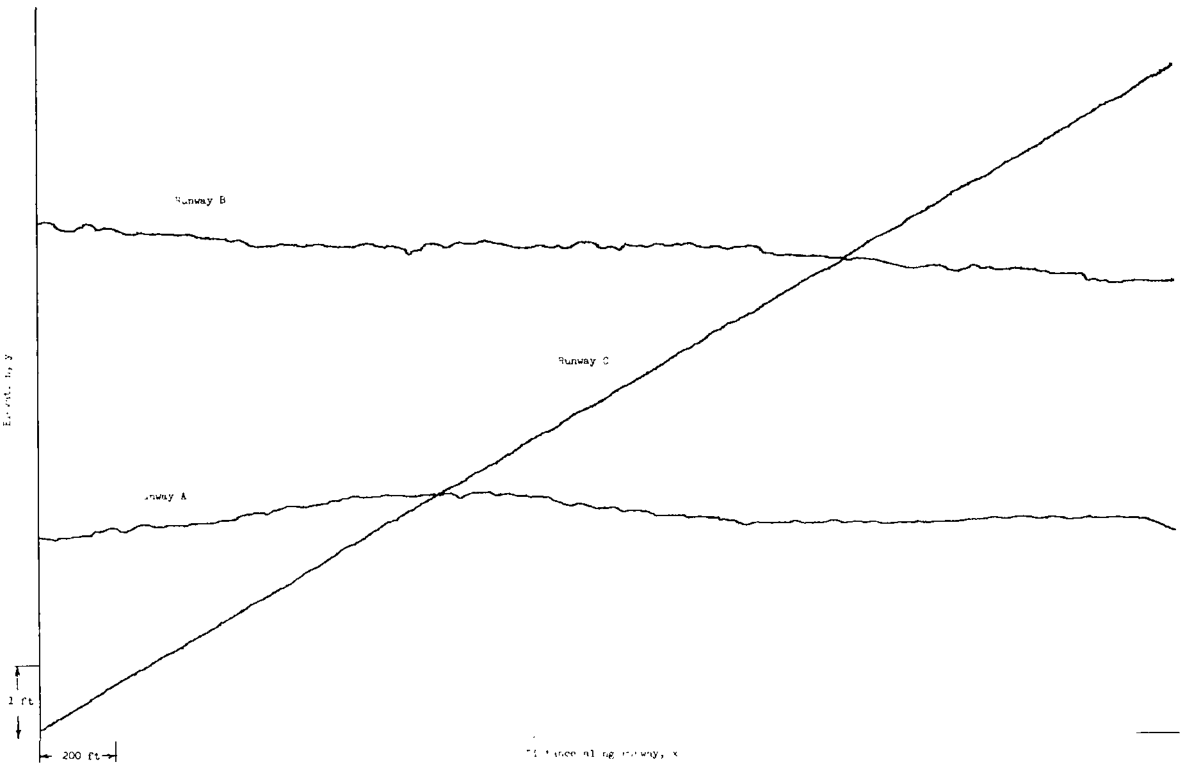



Figure 3.- Elevation profiles for test sections of three runways.

the test section of runway C had a nearly constant 0.3-percent grade. Figure 4 shows an enlargement of a 300-foot-long portion of the test sections. Runway deviations for wavelengths less than about 300 feet are considered important from the standpoint of runway roughness; therefore, the profiles in figures 3 and 4 indicate that runway C is considerably smoother than runways A and B.

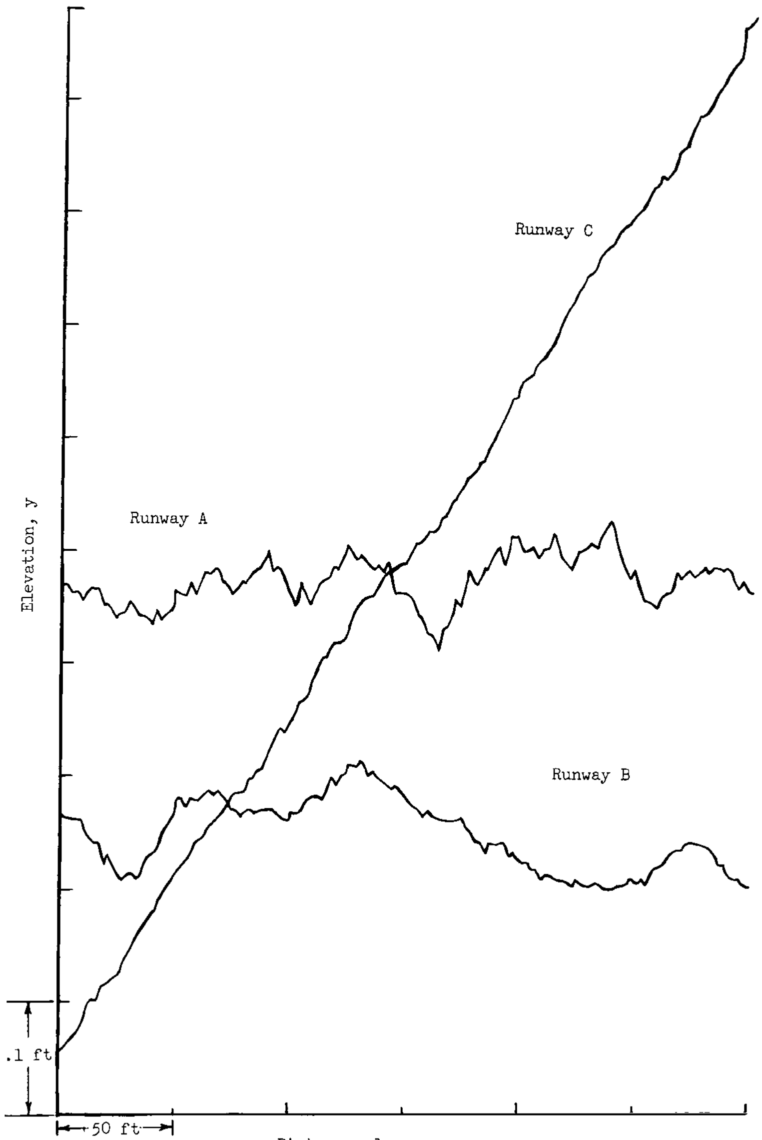



Figure 4.- Elevation profiles for part of test sections of three runways.

Spectra of runway elevation profiles.- The power-spectral-density functions of the three runways are presented in figure 5. The power spectra show the relative contribution of various frequencies, or wavelengths, to the total roughness of the runways. For comparison, the criteria suggested in reference 7 for "new construction" and "needs repair" are also shown in the figure. These criteria indicate, in one case, a roughness level which should not be exceeded in new construction and, in the other case, a roughness level where runway repairs are needed.

The spectra of the three runways (fig. 5) show that the average amplitudes of the roughness increase with increasing wavelengths in a manner similar to that of the criteria spectra. All the runway spectra are below the limits of the suggested criteria for needs repair, and runway C is considerably below the criteria for new construction. On the basis of comparison with the criteria, runway C is expected to be very smooth and is expected to result in low airplane response and in no pilots' complaints.

Central deviations from a straight line.- In order to show the physical size of the roughness deviations in a more easily interpreted form than the spectral presentation, the rms values of the central deviations from a straight line of a given length and of the runway surfaces are shown in figure 6. For comparison, the rms deviations from a straight line corresponding to the suggested roughness criteria (fig. 5) are shown by the two curves in the figure. Inspection of the results shows that, for each runway, the rms deviations are relatively small, being less than 0.012 foot for a straight-line distance of 20 feet and less than 0.039 foot for a distance of 200 feet, for example. In comparison with the two criteria lines, it is seen that each runway is smoother

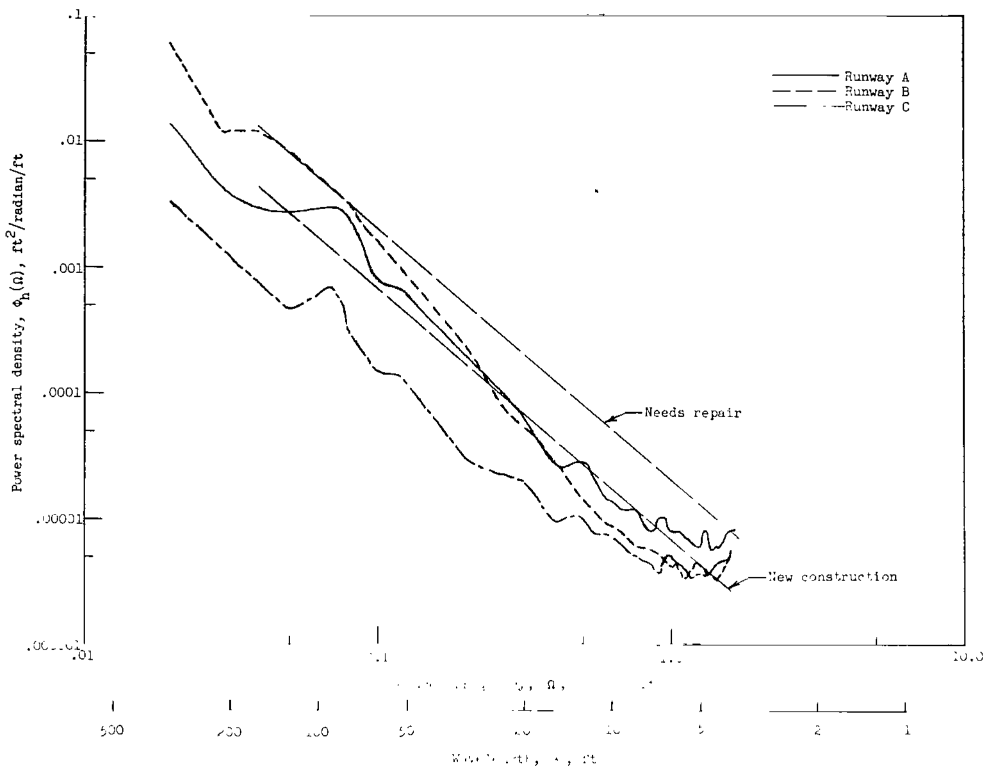



Figure 5.- Power-spectral-density functions for profiles of test sections of runways used in investigation.

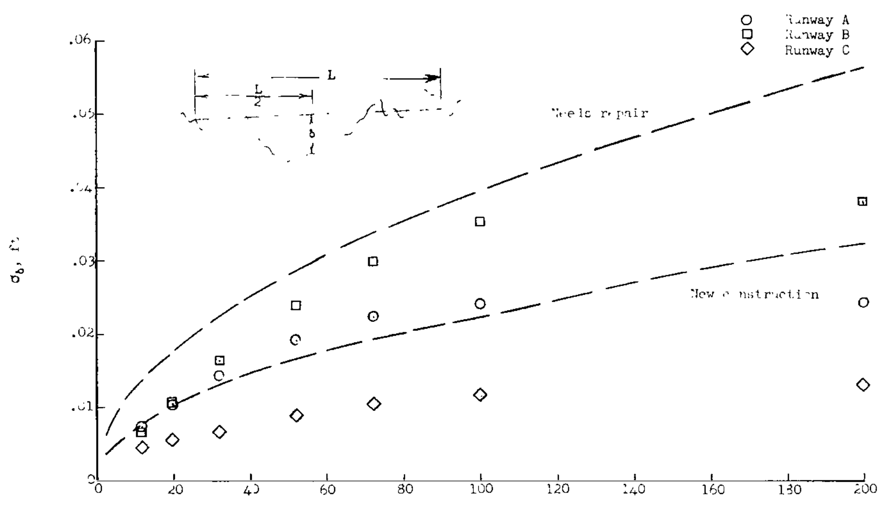



Figure 6.- Root-mean-square values of central deviations between straight lines of various lengths and surfaces of runway test sections.

than the needs-repair criteria and that runway C is the smoothest, being even smoother than the new-construction line. Thus, the relative roughness of the runways as shown by the rms deviations is in the same order as the order indicated by the roughness power spectra previously discussed.

## Acceleration Response

General characteristics.- A profile of a 1,200-foot portion of runway A, together with the normal-acceleration response of the airplane nose and center of gravity as it was taxied over this profile at two speeds, is shown in figure 7. Examination of the figure shows that the accelerations at the nose of the airplane have a somewhat greater amplitude than those at the center of gravity and that the acceleration response at 80 knots was much greater than at 35 knots.

Comparison of the acceleration time history with the runway profile (fig. 7), suggests that there is no simple correlation between responses and runway roughness. Although in some cases a particular acceleration peak can be

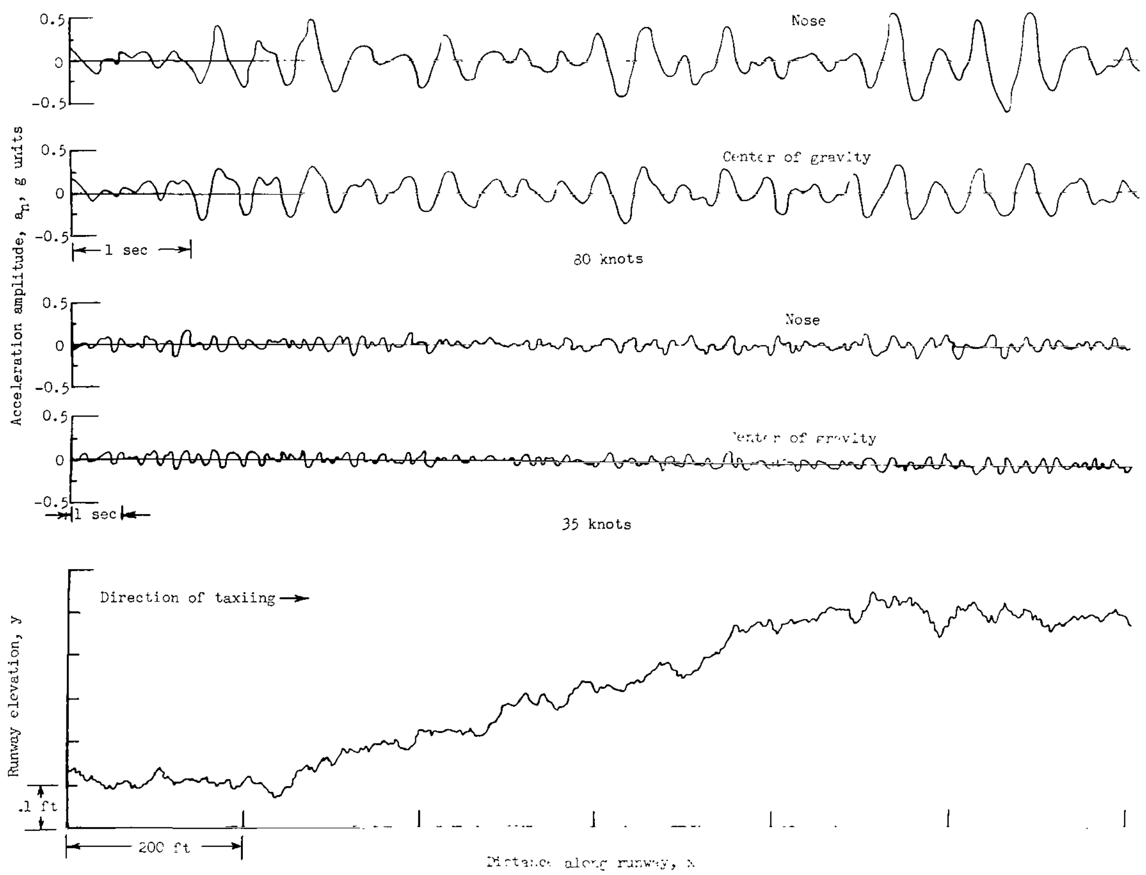
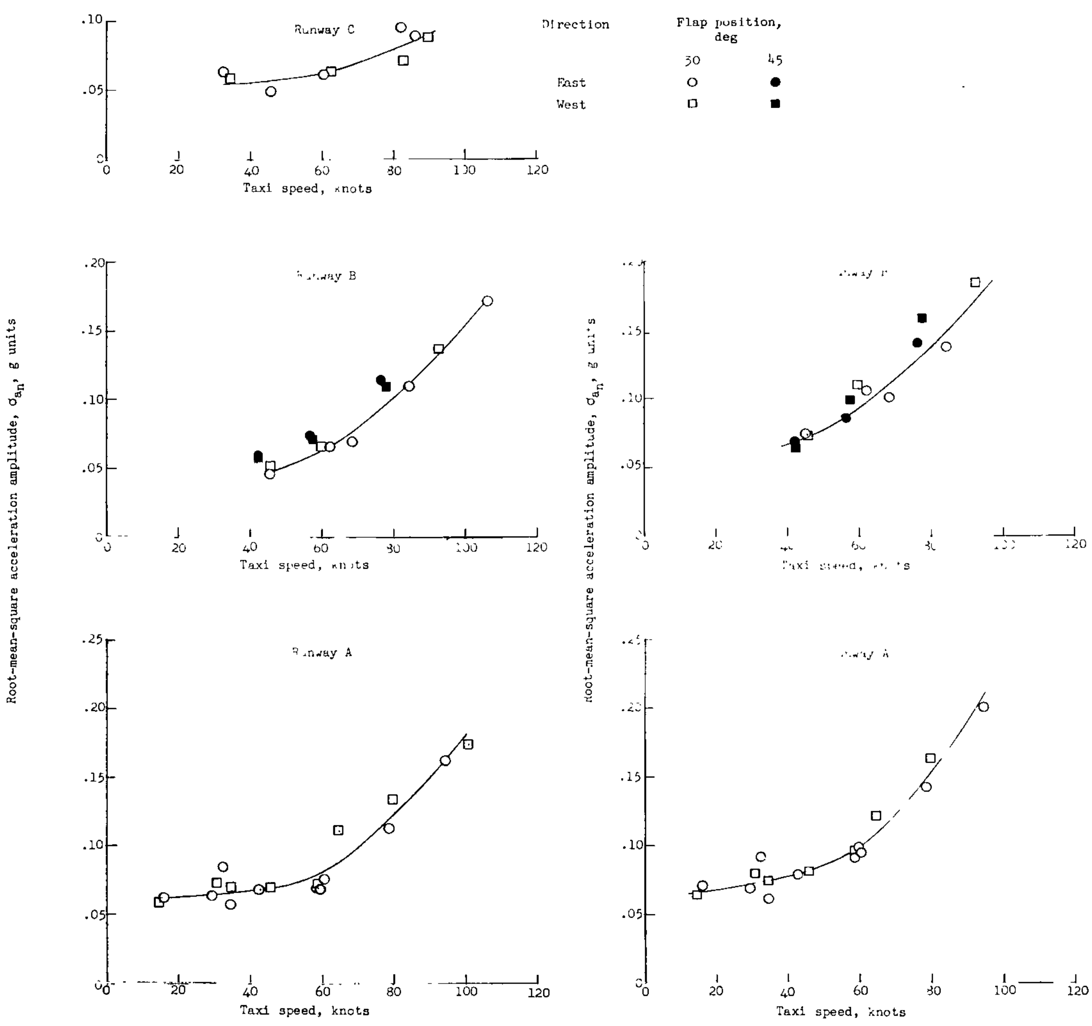



Figure 7.- Runway elevation variation and resulting airplane response for 1,200-foot section of runway A.

associated with a particular area of the runway, in general such association is very difficult. This difficulty stems from the fact that the response is dependent on such factors as shape of the bumps, phasing of the bumps, airplane speed, and response frequencies of the airplane. The effects of these factors are discussed in detail in reference 12, which presents the results of an analog study in which acceleration-response histories of a simplified airplane were compared directly with runway profiles for various taxiing speeds.

Root-mean-square acceleration.- The variation with ground speed of the rms acceleration at the airplane center of gravity and at the nose is shown in figure 8. Circular and square data symbols have been used for acceleration values




(a) Center of gravity.

(b) Nose.

Figure 8.- Variation with speed of root-mean-square values of center of gravity and nose acceleration of test airplane.

to differentiate between the two directions in which the airplane was taxied down the runway. Open data symbols are used to represent the airplane in the take-off configuration with flaps deflected 30°; closed data symbols are used to represent the landing configuration with flaps fully deflected (45°) and dive brakes extended. To indicate the trends of the data, curves have been faired through the data points.

For all three runways, $\sigma_{a_n}$ at the center of gravity and the nose generally increased with speed throughout the speed range. Direction of taxiing had no significant effect on acceleration response. An increase in flap deflection from 30° to 45° tended to increase rms acceleration at the center of gravity and also at the nose.

In order to facilitate comparison of acceleration response at the nose with that at the center of gravity and to show the effect of speed and runway on the response, the faired curves from figure 8 are replotted in figures 9 and 10. As shown in figure 9, the rms acceleration response at the nose was higher than at the center of gravity throughout the speed range on both runways. For example, on runway A the nose response was roughly 25 percent higher than the center-of-gravity response at most speeds, whereas on runway B the nose response varied from 60 percent higher than the center-of-gravity response at 50 knots to 30 percent at approximately 100 knots. The increased response at the nose over that at the center of gravity is due to the pitching motion of the airplane.

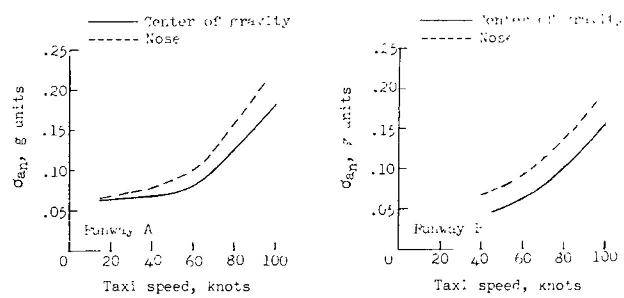
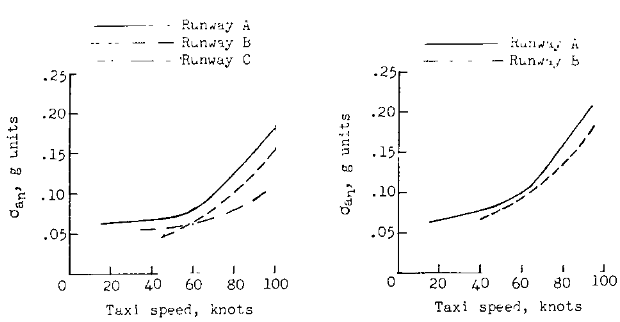



Figure 9.- Comparison of acceleration response at center of gravity and nose of test airplane.

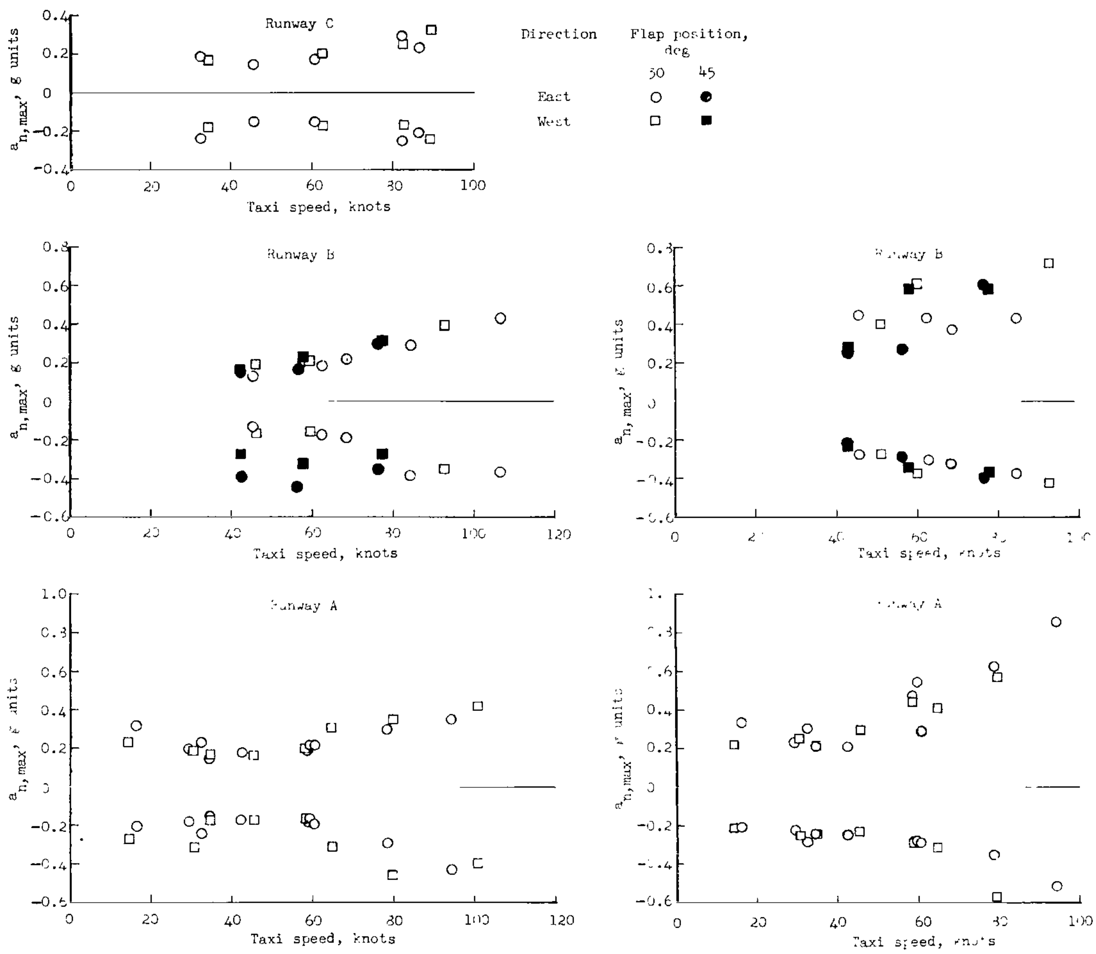



(a) Center of gravity. (b) Nose.

Figure 10.- Comparison of acceleration response on three runways.

The acceleration response at the center of gravity of the airplane was highest for runway A throughout the speed range and lowest for runway C at speeds above 60 knots. (See fig. 10.) Response at the nose was also higher on runway A than on runway B. The low response on runway C is consistent with indications from the profiles and spectral comparisons. (See figs. 3 to 5.) However, the higher response at the center of gravity on runway A than on runway B is not consistent with what would be expected from consideration of the airplane response characteristics and runway spectra. For speeds from 50 to 100 knots and significant airplane-response frequencies from 1 to 6 cps, the range of wavelengths predominantly affecting the response would be from about 14 to 170 feet. Throughout most of this range of wavelengths, however, the runway spectra (fig. 5) indicate that runway B is as rough or rougher than runway A. In this case, for which the spectra showed comparatively small differences in roughness, it appears that the power spectra did not provide a good indication of the relative response experienced by the airplane. Although the reason for the poor correlation of airplane response with runway spectra is not known, it is thought to be due to the inability of the power spectra to account properly for such factors as shape, spacing, and size distribution of the surface irregularities.

Maximum acceleration.- The maximum positive and negative accelerations recorded at the nose and center of gravity for each run are shown in figure 11.




(a) Center of gravity.

(b) Nose.

Figure 11.- Variation of acceleration response of test airplane with taxiing speed.

Although there is some scatter in the data for given speeds, in general, the results show that the accelerations are larger at the nose than at the center of gravity, that they increase with speed, and that they are not appreciably affected by taxi direction. Maximum response on runway C was lower than on either of the other two runways. These trends are, in general, similar to those shown in figures 8 to 10 for the rms accelerations. It may be mentioned that maximum values of about six times the rms values were obtained and that the average ratio of the maximum to rms acceleration was approximately 3 for the center of gravity and $3\frac{1}{2}$ for the nose.

Power spectra of acceleration response.- The power-spectral-density functions of airplane acceleration response from 1/4 to 7 cps on the three runways at various speeds are presented in figures 12 and 13. Values above 7 cps are not presented because of the decreased instrument response and low amplitude of the spectrum above this frequency. Three predominant response frequencies are evident. These are identified as wing bending at about $5\frac{1}{2}$ cps, rigid-body vertical translation from 2 to 3 cps, and at some speeds a rigid-body pitch mode at $1\frac{3}{4}$ cps.

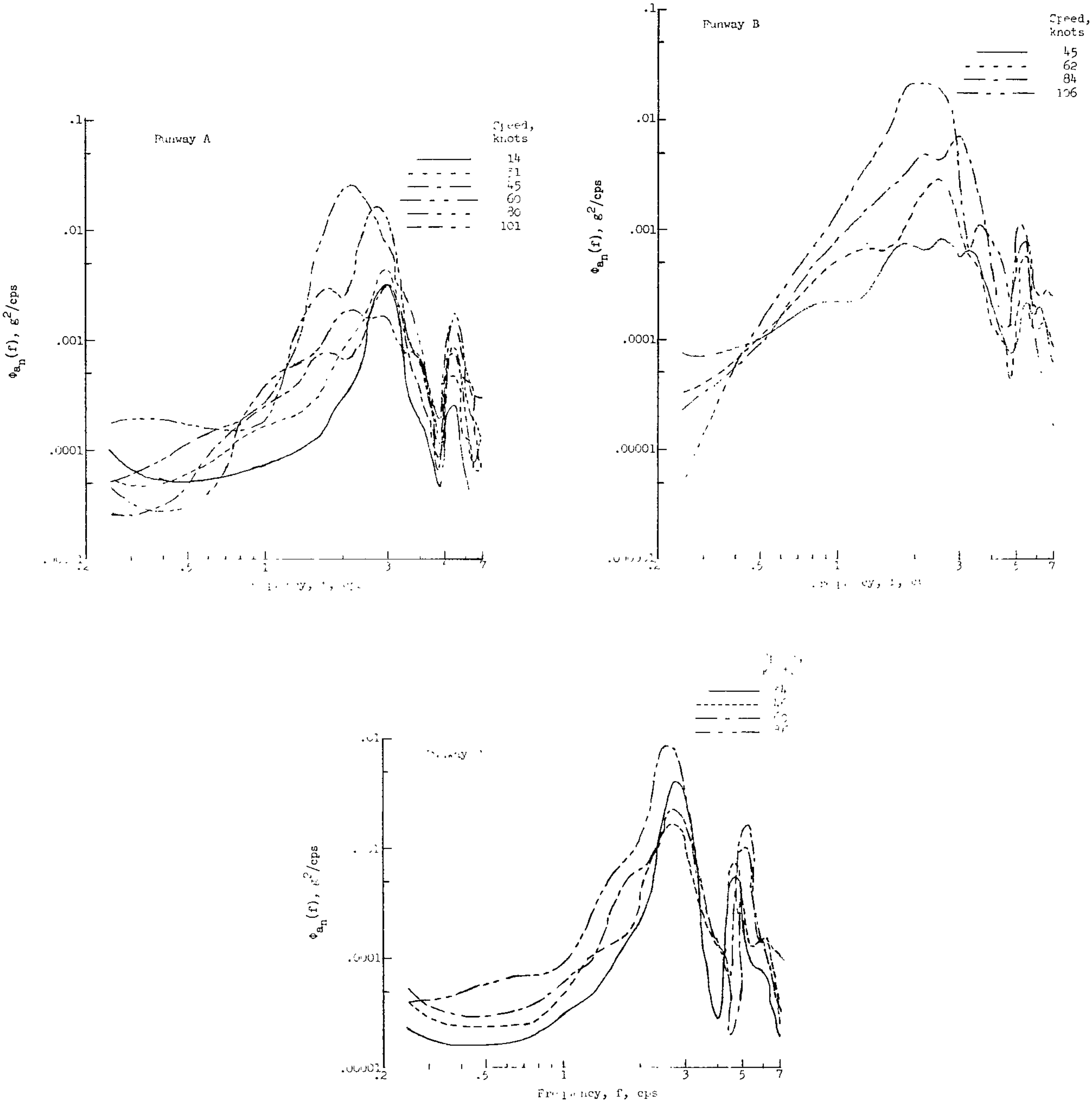
The frequency of the wing bending mode remained constant with speed for the tests on runways A and B, but the frequency of this mode was somewhat lower for the tests on runway C for which some fuel remained in the wing-tip tanks. The vertical translation mode consistently had the highest peak amplitude throughout the speed range. The frequency of this mode decreased from about 3 cps at low speeds to around $2\frac{1}{4}$ cps at high speeds. The pitch mode which generally occurred at about $1\frac{3}{4}$ cps at intermediate speeds was most evident on runway A and was hardly noticeable on runway C. The pitch mode may have been present but merged with the vertical translation mode for some of the spectra.

A comparison of the acceleration spectra at the center of gravity and the nose of the airplane for two speeds on runway A is shown in figure 13. The comparison shown for 60 knots is typical of those throughout the speed range above 15 knots. At approximately 15 knots the two spectra are somewhat similar, but at higher speeds the spectra are consistently higher for the nose than for the center of gravity in the lower frequency range. The increased acceleration spectra for the nose of the airplane is due to the pitch effect and accounts for the higher rms acceleration previously noted for the nose.

## Correlation of Pilot's Evaluation of Runways With

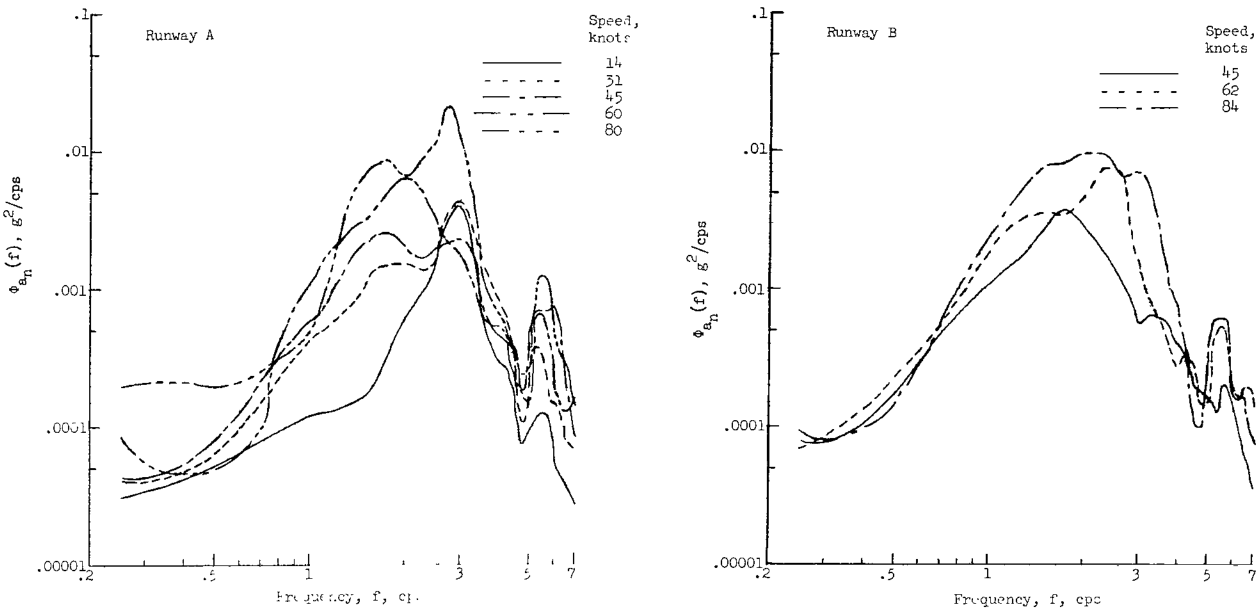
## Acceleration and Runway-Profile Measurements

Pilot opinion of the roughness of the runways used in this investigation is valid only for the test aircraft. The pilot considered all three runways to be generally acceptable but noted a considerable difference in their roughness characteristics. He rated runway A as moderately rough, runway B as



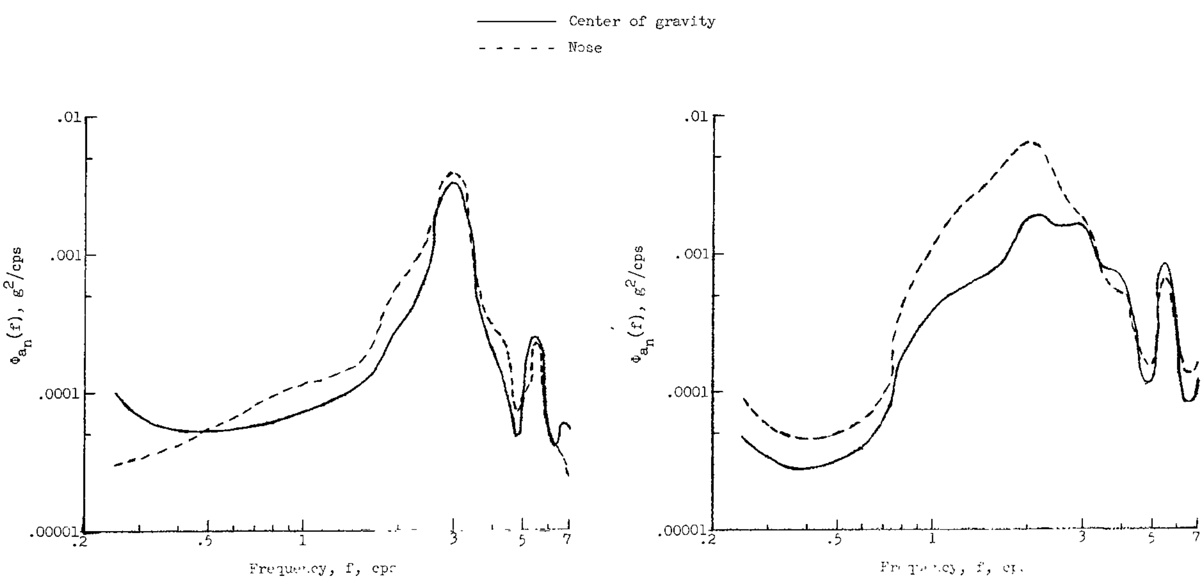

(a) Center-of-gravity acceleration.

Figure 12.- Power-spectral-density function of airplane response on runways at various speeds.




(b) Nose acceleration.

Figure 12.- Concluded.




(a) 15 knots.

(b) 60 knots.

Figure 13.- Comparison of power-spectral-density functions of airplane acceleration at center of gravity and nose for runway A.

somewhat smoother than runway A, and runway C as the smoothest of the three runways. The projection of material above the joints of the surface of runway A gave a washboard effect which resulted in annoying vibrations of the instrument panel and other equipment in the cockpit area. These vibrations were partially aggravated by the test procedure of holding the nose wheel down at high speeds. A few shallow dips were felt on runway B, but these were not as objectionable as the motion experienced on runway A. Runway C was considered to be smooth although the joints in the surface could be detected.

The pilot's evaluation of the relative roughness of the runways was consistent with measurements of airplane response in that accelerations were generally highest on runway A, somewhat lower on runway B, and lowest on runway C. His evaluation of runway C as the smoothest runway was also consistent with the runway spectra.

## Transfer Functions

The frequency-response functions of the airplane center-of-gravity acceleration to runway roughness are shown in figure 14 for four test runs on runway A. The speeds for the four runs varied from 29 to 35 knots. Except for these relatively small differences in speeds, the data were essentially for the same test conditions. Examination of the results in figure 14 shows that the four frequency-response functions are in good agreement as regards the frequencies at which the predominant peak amplitudes occur. However, differences of approximately 3 factors exist in the peak amplitudes for the major response peak at about 3 cps. These differences cannot be attributed to the small differences in speed for the four runs. The large variations noted in the frequency-response functions shown in figure 14 are typical of the results obtained on the two other runways and also on runway A at other speeds. Detailed examination of the various transfer functions did not reveal any consistent trend in the peak amplitudes with runway roughness level or with airplane speed. Thus, it is evident that the transfer function obtained as the ratio of the airplane acceleration spectrum

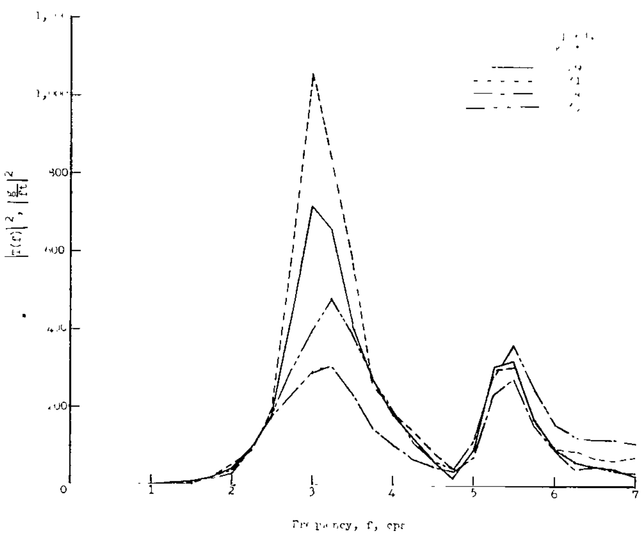


Figure 14.- Frequency-response functions of airplane center-of-gravity acceleration for taxi runs on runway A.

to the runway roughness spectrum is of doubtful applicability, at least for the airplane of this investigation.

Although the previously discussed errors in both the acceleration and roughness spectra could cause some differences between the frequency-response functions for repeated runs, analyses indicated that these differences would be much smaller than those actually present in the results shown in figure 14. It is thought, therefore, that other factors must account for the inconsistent results obtained. These factors include: (1) inadvertent airplane deviations from the intended taxi track along the surveyed runway center line, (2) the nonlinear response characteristics of the landing gear, and (3) the use of a single input rather than three inputs to represent the roughness.

## CONCLUDING REMARKS

An investigation has been conducted to determine the acceleration-response characteristics of a jet trainer airplane and to correlate them with runway roughness while the airplane was taxiing at various constant speeds up to 100 knots on three runways having different roughness characteristics.

Airplane root-mean-square (rms) acceleration values increased with speed and were not significantly affected by the direction of taxiing on the runways. The rms acceleration response at the nose was higher than that at the center of gravity throughout the speed range on both runways for which response was measured at the nose.

Two predominant frequency-response modes were evident from acceleration response spectra, vertical translation from 2 to 3 cps, and wing bending at $5\frac{1}{2}$ cps for empty wing-tip fuel tanks. In addition, a pitching mode was evident at certain speeds at approximately $1\frac{3}{4}$ cps.

Pilot opinion regarding the relative roughness of the three runways was in agreement with airplane-acceleration-response measurements. Airplane response and runway spectra were in general agreement in that the lowest response was measured on the runway which was indicated by the profile spectra to be significantly smoother than the other two. However, the runway spectra did not provide a good indication of the relative response of the airplane on the other two runways for which the spectra showed only a small difference in roughness. The reason for the poor correlation of airplane response with runway spectra is thought to be due to the inability of the power spectra to account properly for such factors as shape, spacing, and size distribution of the surface irregularities.

Airplane transfer functions computed from the ratio of the output airplane acceleration spectra to the input runway spectra varied significantly between repeated runs for similar test conditions and did not define a unique transfer function which was reasonably independent of input amplitude and airplane speed.

Consequently, the applicability of such transfer functions, at least for this airplane, appears to be questionable.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 30, 1963.

## REFERENCES

1. Walls, James H., Houbolt, John C., and Press, Harry: Some Measurements and Power Spectra of Runway Roughness. NACA TN 3305, 1954.

2. Houbolt, John C., Walls, James H., and Smiley, Robert F.: On Spectral Analysis of Runway Roughness and Loads Developed During Taxiing. NACA TN 3484, 1955.

3. Potter, Dexter M.: Measurements of Runway Roughness of Four Commercial Airports. NACA RM L56I26, 1957.

4. Thompson, Wilbur E.: Measurements and Power Spectra of Runway Roughness at Airports in Countries of the North Atlantic Treaty Organization. NACA TN 4303, 1958.

5. Houbolt, John C.: Progress and Recommended Research Activity on the Runway Roughness Problem. Presented at the Structures and Materials Panel of AGARD (Copenhagen, Denmark), Oct. 20-29, 1958.

6. Milwitzky, Benjamin: Study of Taxiing Problems Associated With Runway Roughness. NASA MEMO 2-21-59L, 1959.

7. Houbolt, John C.: Runway Roughness Studies in the Aeronautical Field. Jour. Air Transport Div., Proc. American Soc. Civil Eng., vol. 87, no. AT 1, Mar. 1961, pp. 11-31.

8. Morris, Garland J., and Stickle, Joseph W.: Response of a Light Airplane to Roughness of Unpaved Runways. NASA TN D-510, 1960.

9. Neuls, G. S., Maier, H. G., Lerwick, T. R., Robb, E. A., and Webster, I. J.: Optimum Fatigue Spectra. ASD Tech. Rep. ASD-TR-61-235, U.S. Air Force, Apr. 1962.

10. Press, Harry, and Tukey, John W.: Power Spectral Methods of Analysis and Their Application to Problems in Airplane Dynamics. Vol. IV of AGARD Flight Test Manual, Pt. IVC, Enoch J. Curbin, ed., North Atlantic Treaty Organization (Paris), pp. IVC:1 - IVC:41.

11. Coleman, Thomas L., Press, Harry, and Meadows, May T.: An Evaluation of Effects of Flexibility on Wing Strains in Rough Air for a Large Swept-Wing Airplane by Means of Experimentally Determined Frequency-Response Functions With an Assessment of Random-Process Techniques Employed. NASA TR R-70, 1960. (Supersedes NACA TN 4291.)

12. Hall, Albert W., and Kopelson, Sheldon: The Location and Simulated Repair of Rough Areas of a Given Runway by an Analytical Method. NASA TN D-1486, 1962.



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